Estimation Of Uranium Production In North Korea Through Satellite Image Analysis

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ABSTRACT
In the early 1990s, South and North Korea made a Joint Declaration of Denuclearization of the Korean Peninsula. Nevertheless, North Korea has continued to develop nuclear weapons. According to 38North(North Korean Intelligence Project in the United States), in March 2021, 38North discovered signs of restarting North Korean nuclear facilities through satellite imagery. North Korea has nuclear material through various nuclear facilities and uses them for nuclear weapons, but does not disclose it to the international community. Therefore, it is necessary to estimate the amount of nuclear material in North Korea for peace and security on the Korean Peninsula. In this study, the uranium production at the Pyeongsan Mine that has a lot of uranium reserves was estimated by applying the satellite image analysis method. The contaminated area of mill tailings ponds that collect tailing after the uranium ore process among the Pyeongsan mine nuclear facilities was analyzed. To calculate the amount of uranium mill tailings, the ponds depth was assumed based on statistical data of lakes and reservoirs on the in Korea. In addition, the Uranium grade was estimated by applying a range of 0.15 to 0.9% for comparison with the results of similar research methods. As a result of the calculation using the above conditions, the production amount of uranium (U_3O_8) was estimated to be about 7 ~ 497 ton. This result is low compared to about 273 to 886 tons estimated by James Martin's research team in the United States (ESRADA methodology using ore facilities scale) and about 187 to 786 tons estimated by the Nautilus research team (Top-down methodology). The above two research institutes evaluated conservatively by assuming the maximum size and maximum operation rate of ore facilities(CCDs). The reason that the uranium production in this study was underestimated compared to the other two studies was that the depth of the pond was used as the statistics. The results of this study can be used as basic data for estimating the production of enriched uranium or Pu in North Korea.

INTRODUCTION
Nuclear weapon testing by North Korea began in 2006 and continued to its sixth test in 2017. According to USGS National Earthquake Information Center, the sixth nuclear test was five times more powerful than the fifth [1]. These nuclear activities by North Korea pose a threat to security for both South Korea and worldwide. Hence, following the nuclear tests by North Korea, the United States is trying to denuclearize North Korea by holding a

summit with the North to manage and restrict their nuclear threats. In the case where denuclearization proceeds, fundamental research is necessary to verify North Korea's nuclear activities and verify denuclearization.

Through satellite imagery, experts from 38North continuously monitor the nuclear facilities in North Korea to verify if they are in operation. Recently, 38North analyzed satellite imagery and identified signs of the nuclear facilities restarting. As such, analysis using satellite imagery to determine the signs of operation of nuclear facilities is a good method to confirm the level nuclear activity of the North when there is a limited access to information about their nuclear development. In this study, uranium production from the uranium mine was estimated by analyzing satellite imagery from the North Korea's nuclear development period, then the obtained production estimates were compared to those from the other experts.

BACKGROUND

Overview and Current Status of North Korean Uranium Mine

Uranium found in North Korea are generally mined in the form of monazite rock or phosphate minerals such as thorium. The total uranium reserve in North Korea is estimated to be about 26 million tons, and of these, it is estimated that 4 million tons of reserves are economically viable [2].

Grade of Uranium

The uranium grade is a major factor for estimating production output and the grade of uranium mine in its natural state varies from 0.1% to 10%. According to the investigation by Soviet Union in the 1960 ~ 70s, grade of uranium ores from Sunchon Mine and Pyongsan Mine in North Korea was found to be very low. In 1980, North Korea revealed themselves that their uranium grade is in the range 0.3 ~ 0.5% U_3O_8 [4]. However, recent analysis from 38North estimated uranium ore content from Sunchon Mine and Pyongsan Mine to be 0.086% and 0.26%, respectively [3].

Mining Uranium

Method for mining uranium is selected based on conditions such as how deep the orebodies are located and uranium grade, and some of the mining methods include open pit, underground, and in-situ leaching (ISL). Open pit mining is applied where the uranium ores are near the surface and is employed where ores can be mined right away through removal of soil layer covering the ores when the uranium mine is identified on the surface. An advantage of open pit mining method is that it is less expensive. Underground mining uses tunnels and shafts to access uranium ores located at a few dozen meters underground, and this method accounts for about 30% of the mined uranium produced worldwide. ISL mining method involves drilling a well into the ground to the point where the ore deposit is located, then injecting acid through the pipe to dissolve uranium from the ore deposits, then pumping up the leached uranium to the surface via a separately installed recovery well to be further refined. Typically, uranium grade is not too high and falls within 0.1%, and this method is selected for the mines with the rock solid ground at the mine [5]. Uranium mine from North Korea is known to be from black shale, mainly located at a depth of 200 m underground, primarily mined with the underground mining method [6].

North Korea's Major Uranium Mine

Pyongsan is a representative uranium mine in North Korea and about 10,000 tons of uranium is produced every year through underground mining. Uranium production initiated in 1950s, but no large quantities of uranium being mined until the 1970s, followed by active mining starting from 2010s, as per the estimates. Uranium grade is 0.26% and is used to produce uranium yellowcake (U_3O_8) or uranium dioxide (UO_2) [7].

Selection of Estimate Target

Jeffrey Lewis, who is the director of James Martin Center for East Asia Nonproliferation Program in United States, analyzed satellite images of 2015 Pyongsan Mine from 38North to determine contamination of mill tailings ponds [8]. Pyongsan Mine, amongst other North Korea's uranium mines, is estimated to be under active development from the 2000s, and there are clear indications of the mines being used up to recently (Figure 1) [9]. Comparing the past satellite imagery for Pyongsan uranium mines, a continuous increase in the uranium mining remnants as well as an increase in the uranium mill tailings ponds are evident. (Figure 2) The past satellite imagery was obtained through 'Historical Imagery' function from Google Maps and continuous operation of mines was confirmed by the past satellite imagery from 2011 and onwards. With this, this study estimated the uranium production volume for Pyongsan mines.

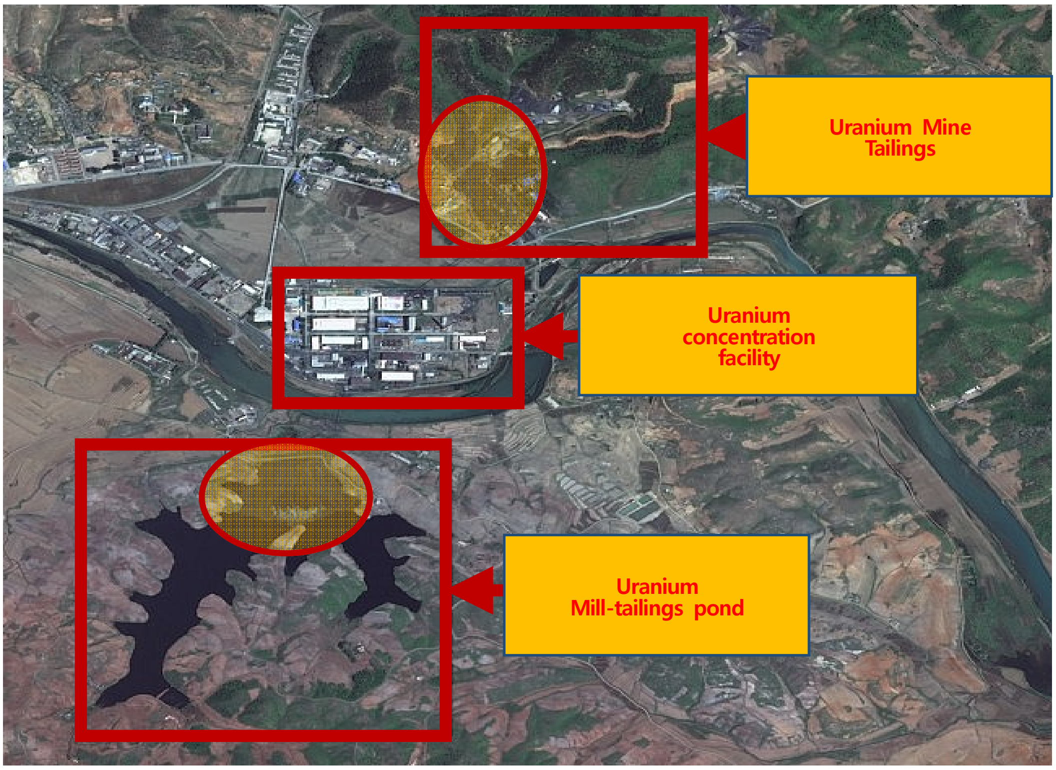

Fig 1. Signs of uranium production at Pyongsan Mine

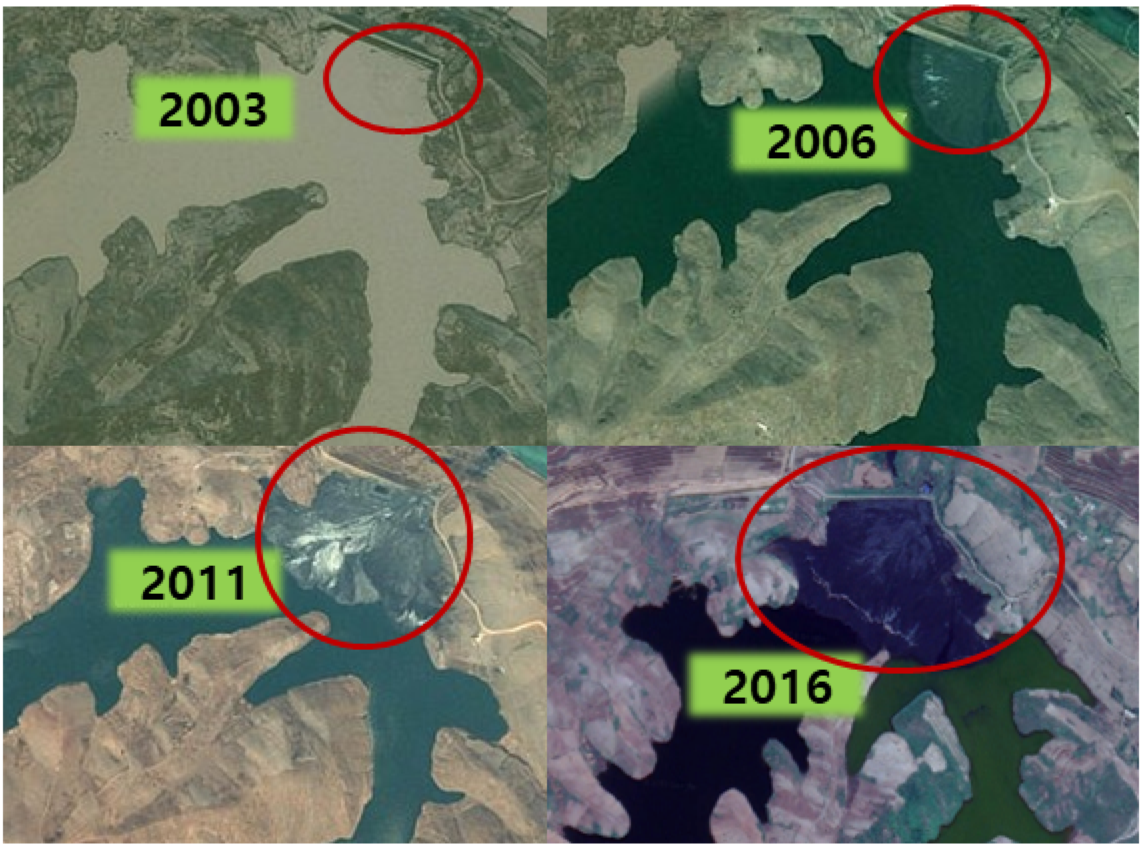

Fig 2. Changes in Contaminated Area by Year of Mill Tailing Ponds

METHOD

To estimate the uranium production volume, coordinates of Pyongsan mines (38°19′4.56″N, 126°25′57.43″E) was applied [10] and satellite imagery was analyzed according to various time periods. Amount of mill tailing ponds from uranium refining process was estimated through analysis using satellite imagery and uranium production volume was calculated by back estimation. The calculation process followed the order of (Figure 3):

1) Mill tailings pond area calculation by analyzing satellite imagery
2) Depth calculation based on lake statistics
3) Amount of uranium calculated by applying uranium grade
4) Back calculation to obtain the production volume by using the density and concentration of the concentrates

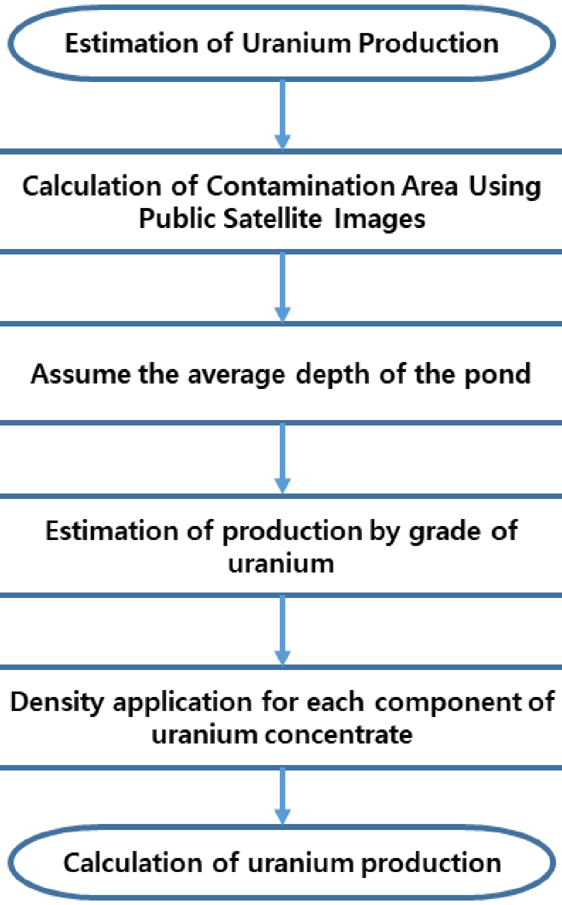

Fig 3. Flowchart for uranium production estimation method

Additional Assumptions

Assuming that the total amount of mill tailings generated from mining operations are dumped to the tailings pond, the volume and composition of mill tailings ponds and the uranium grade were assumed as following for the calculation.

1) Volume of mill tailings pond

Mill tailings pond for Pyongsan mines have dams built in the direction of the river but its shape is deemed to be a commonly formed natural lake. The minimum and maximum lake depth was obtained by referencing statistical depth data from 24 natural lake and reservoir among 178 lake and reservoir in Korean peninsula and the minimum and maximum values were employed as the lake depth value [11](Table 1).

Table 1. Current status of natural lakes in Korea

Reservoir	Type	Average Depth (m)
Namyang	fresh water	4.1
Pyeongtaek	fresh water	4.07
West	fresh water	1.72
Jilnalbul	natural, fresh water	2
Upo Wetland	natural, fresh water, dam	1.5
Nakdong River Estuary	fresh water	5
sapkyo	fresh water	2.5
Sukmoon	fresh water	3.6
Geumgang	fresh water	6.5
Hwajinpo	lagoon	1.3
Songji	lagoon	0.9
Hyang	Brackish	4.8
Mae	lagoon	2
Gyeongpo	Brackish	1.5
Youngrang	lagoon	4
Chungcho	lagoon	4
Moonchunji	fresh water, natural	6.3
Suryong	fresh water	2.3
Seungun2	fresh water	3
Pusa	fresh water	3.5
Pyungjeun	fresh water	2.7
Gamhong	fresh water	2.1
Sungam	fresh water	1.3
Backgok	fresh water	10.5
Avg.		**3.38**
Max.		**10.5**
Min.		**0.9**

2) Composition of mill tailings pond

Composition of uranium mill tailings pond can differ according to composition of the raw ore, the mining method, and uranium refining operations. Based on the typical composition of uranium concentrates, this study assumes that the material is present in a dry state [12](Table 2).

Table 2. Composition of dry uranium concentrate

Composition	ratio (%)
U_3O_8	74.8
SiO_2	3.4
Cl^-	0.27
SO_4^{-2}	0.52
P_2O_5	0.11
Fe	0.38
Ca, Mg	6.31
Th	0.03
Rare earth elements	0.13
Density	**8.38 g/cm^3**

3) Uranium grade

As an important variable for determining uranium production volume, uranium grade was assumed to be 0.28% as researched previously. In addition, to allow a comparison with the estimates from other experts, minimum grade of 0.15% and maximum grade of 0.9% was also used for calculation.

RESULT

Volume of mill tailings pond according to the contaminated area of the pond

Contaminated area of the Pyongsan mill tailings pond in 2018 was calculated by the area calculation tool shown in the satellite imagery, and the area was calculated to be about 88,241 m^2.

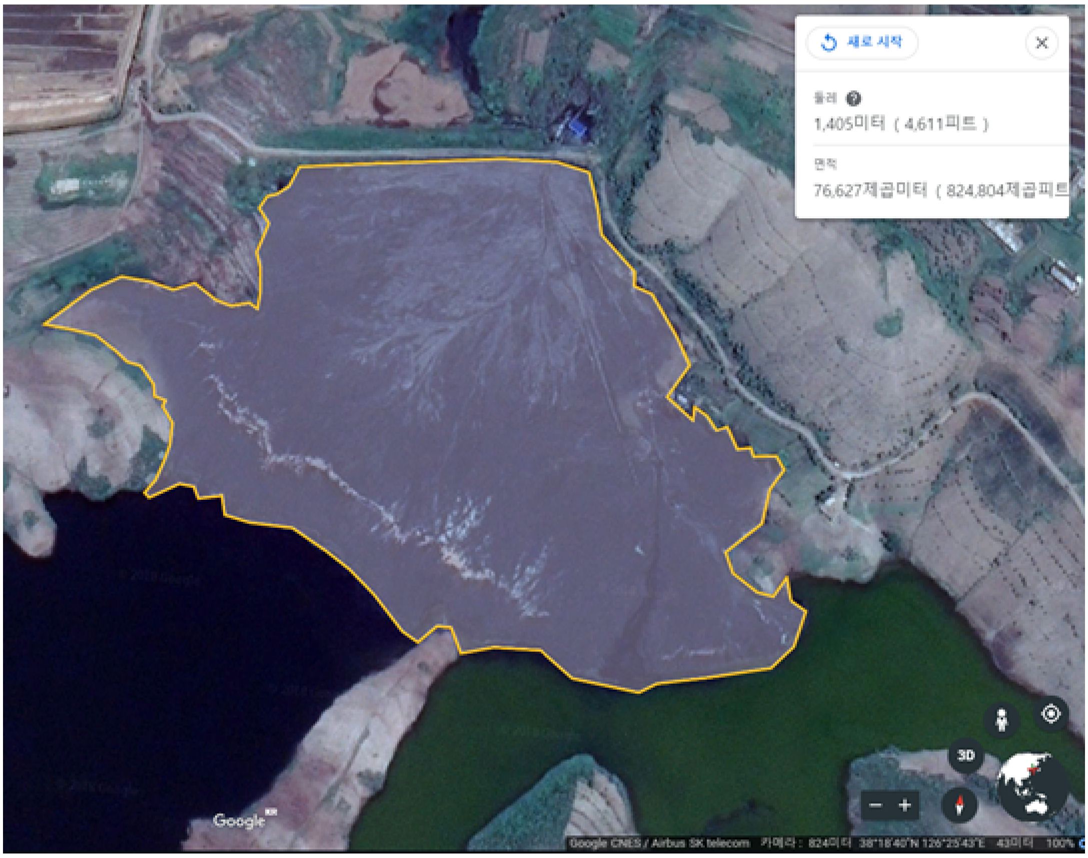

Fig 4. Calculation of polluted area of Milltailings pond in Pyeongsan in 2018 using the area calculation tool

Based on the area calculated above, mill tailings pond volume was estimated by using the average (3.38 m), minimum (0.9 m) and maximum (10.5 m) depth of lake. The pond volume was calculated to be 79,417 m^3 and 926,531 m^3, when using minimum depth and maximum depth, respectively.

Pyongsan Mine – Estimated Uranium Production Volume

By using the range of uranium ore grades and the contaminated volume for mill tailings ponds, the amount of uranium per volume was calculated. As well, by applying the amount of uranium concentrate in the natural state and the proportion of elements in the composition of uranium concentrate, amount of uranium trioxide was calculated. Here, when using the average lake depth value and uranium grade of 0.28%, about 49 tons of uranium production is estimated.

Table 3. Estimated results of uranium production

Division	Depth(m)	mill tailings amount (m^3)	Volume according grade of Uranium ore (m^3)			U_3O_8 (ton) U-235 0.7%		
			0.15%	0.28%	0.9%	0.15%	0.28%	0.9%
Avg.	3.38	298,255	447	835	2,684	26	49	159.9
Max.	10.5	926,531	1,389	2,594	8,338	82	154	496.8
Min.	0.9	79,417	119	222	714	7	13	42.6

Estimated Production Volume from Other Overseas Experts

Nautilus Institute, a research institute in the United States, and James Martin Center estimated the uranium production volume in North Korea. Estimate from James Martin Center was based on Bakcheon and Pyongsan mines, using the uranium grade range of 0.26% ~ 0.8%. They tried to estimate based on size of the uranium mining facility, but because there was no external mining facility, the size of the building was used instead. Hence, estimate from this method is conservative and might be an overestimation. On the other hand, Nautilus Institute used top-down method by estimating backwards assuming enriched uranium amount, and bottom-up method by assuming a uranium mining capacity. The estimates were obtained by using uranium ore grade of 0.15% ~ 0.9%. However, since both methods make assumptions regarding the conditions and are based on estimates from data, the uncertainty in the estimate is inherent [13],[14]. In order to compare the estimates from Nautilus Institute, James Martin Center, and those from this study, uranium grade of 0.15% ~ 0.9% and maximum lake depth value was used. (Table 4)

Table 4. Production by grade according to uranium production estimation method

Grade of Uranium ore [%]	Uranium production [ton]			
	Milltailings ponds	CCDs	Top-Down	Bottom-Up
0.25	119.8	136.5	-	-
0.8	383.5	443	-	-
0.15	71.9	-	93.5	61.5
0.9	431.5	-	393	3485

CONCLUSIONS

Different uranium production volume was obtained depending on the calculation method and the conditions applied. Ccds method from James Martin Center and top-down approach by Nautilus Institute for estimates based on Pyongsan mine were similar to the production volume obtained from analyzing the mill tailings pond. When estimating using bottom-up approach from Nautilus Institute, uranium production volume with a wide range was obtained.

Mill tailings pond analysis method from this study attempted to use satellite imageries to perform the estimation with integrating some objectivity; but there is a need for a better lake depth estimate. The estimated uranium production volume data from this study and other experts can be used in the future for the safe decommissioning of North Korean uranium mines.

ACKNOWLEDGMENTS

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